

# Steps to Reconcile Inflationary Tensor and Scalar Spectra

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The recent BICEP2 B-mode polarization determination of an inflationary tensor-scalar ratio  $r = 0.2^{+0.07}_{-0.05}$  is in tension with simple scale-free models of inflation due to a lack of a corresponding low multipole excess in the temperature power spectrum which places a limit of  $r < 0.11$  (95% CL) on such models. Single-field inflationary models that reconcile these two observations, even those where the tilt runs substantially, introduce a scale into the scalar power spectrum. To cancel the tensor excess, and simultaneously explain the excess already present in  $\Lambda$ CDM, ideally the model should introduce this scale as a relatively sharp transition in the tensor-scalar ratio around the horizon at recombination. We consider models which generate such a step in this quantity and find that they can improve the joint fit to the temperature and polarization data by up to  $2\Delta \ln \mathcal{L} \approx -17$  without changing cosmological parameters. Precision E-mode polarization measurements should be able to test this explanation.

## I. INTRODUCTION

The recent BICEP2 measurement of a tensor-scalar ratio  $r = 0.2^{+0.07}_{-0.05}$  from degree scale B-mode polarization of the cosmic-microwave background (CMB) [1] is in “moderately-strong” tension with slow-roll inflation models that predict scale-free, albeit slightly tilted ( $1 - n_s \ll 1$ ) power-law power spectra. This tension is due to the implied excess in the temperature spectrum at low multipoles which is not observed and restricts  $r < 0.11$  (95% CL) in this context [2].

These findings can be reconciled in the single-field inflationary paradigm by introducing a scale into the scalar power spectra to suppress power on these large-angular scales. For example a large running of tilt,  $dn_s/d \ln k \sim -0.02$ , is possible as a compromise [1]. Here the scale introduced is associated with the scalar spectrum transiently passing through a scale-invariant slope near observed scales. However, such a large running is uncomfortable in the simplest models of inflation which typically produce running of order  $\mathcal{O}[(1 - n_s)^2]$ . Moreover, a large running also requires further additional parameters in order that inflation does not end too quickly after the observed scales leave the horizon [3].

The temperature anisotropy excess implied by tensors is also not a smooth function of scale, but rather cut off at the horizon at recombination. To counter this excess, a transition in the scalar power spectrum that occurs more sharply, though coincidentally near these scales, would be preferred. Such a transition can occur without affecting the tensor spectrum if there is a slow-roll violating step in the tensor-scalar ratio while the Hubble rate is left nearly fixed. In this work we consider the effects of placing such a feature near scales associated with the horizon at recombination, thereby suppressing the scalar spectrum on large scales.

This slow-roll violating behavior also produces oscillations in the power spectrum [4, 5] and generates enhanced non-Gaussianity [6, 7] if this transition occurs in

much less than an efold. For transitions that alleviate the tensor-scalar tension, these oscillations would violate tight constraints on the acoustic peaks and hence only transitions that occur over at least an efold are allowed. The resulting non-Gaussianity is then undetectable [8, 9]. Throughout, we work in natural units where the reduced Planck mass  $M_{\text{Pl}} = (8\pi G_N)^{-1/2} = 1$  as well as  $c = \hbar = 1$ .

## II. STEP SOLUTIONS

In slow roll inflation, the tensor power spectrum in each gravitational wave polarization state is directly related to the Hubble scale during inflation

$$\Delta_{+,\times}^2 = \frac{H^2}{2\pi^2}, \quad (1)$$

whereas the scalar or curvature power spectrum is given by

$$\Delta_{\mathcal{R}}^2 = \frac{H^2}{8\pi^2 \epsilon_H c_s}, \quad (2)$$

where  $\epsilon_H = -d \ln H / d \ln a$  and  $c_s$  is the sound speed, yielding a tensor-scalar ratio  $r = 4\Delta_{+,\times}^2 / \Delta_{\mathcal{R}}^2 = 16\epsilon_H c_s$ . The addition of a nearly scale invariant tensor spectrum to the CMB temperature anisotropy produces excess power below  $\ell \approx 100$  which at  $r = 0.2$  is difficult to accommodate in slow roll inflation where the scalar spectrum is, to a good approximation, a scale-free power law (see Fig. 1).

The scalar power spectrum can be changed largely without affecting the tensors if the quantity  $\epsilon_H c_s$  changes while  $\epsilon_H$  remains small. As shown in Fig. 1, the excess power resembles a step in this quantity on scales near the horizon at recombination. Hence to alleviate the tension between the tensor inference from the BICEP2 experiment,  $r = 0.2^{+0.07}_{-0.05}$ , and the upper limits from the combined CMB temperature power spectrum  $r < 0.11$  (95%

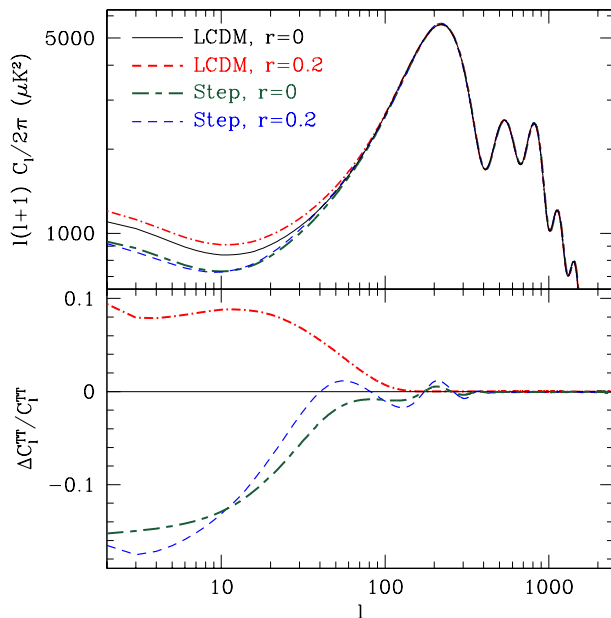


FIG. 1. Total temperature power spectra showing the unobserved excess produced by adding tensors of  $r = 0.2$  to the best fit 6 parameter  $\Lambda$ CDM model and its removal by adding a step in the tensor-scalar parameter  $\epsilon_{Hc_s}$ . Planck data in fact favor removing more power than the tensor excess, preferring a step even if  $r = 0$ . Step model parameters are given in Tab. I.

CL), we examine models where there is a step in this quantity. In this paper we quote  $r$  at the scalar pivot of  $k = 0.05 \text{ Mpc}^{-1}$  where it is unaffected by changes to the scalar power spectrum that we introduce.

As an example, we consider a step in the warp

$$T(\phi) = \frac{\phi^4}{\lambda_B} \left\{ 1 + b_T \left[ \tanh \left( \frac{\phi - \phi_s}{d} \right) - 1 \right] \right\} \quad (3)$$

of Dirac-Born-Infeld (DBI) inflation<sup>1</sup> [10, 11] with the Lagrangian

$$\mathcal{L} = \left[ 1 - \sqrt{1 - 2X/T(\phi)} \right] T(\phi) - V(\phi), \quad (4)$$

where the kinetic term  $2X = -\nabla^\mu \phi \nabla_\mu \phi$ , the sound speed

$$c_s(\phi, X) = \sqrt{1 - 2X/T(\phi)}. \quad (5)$$

Here  $\{b_t, \phi_s, d\}$  parameterize the height, field position and field width of the step while the underlying parameters  $\lambda_B$  and the inflaton potential  $V(\phi)$  are set to fix  $n_s$  and  $A_s$  [12]. In Ref. [13], we showed that such a model

<sup>1</sup> Of course, we are well outside the region of validity of UV complete versions of DBI inflation. However, this is merely a phenomenological proof of principle rather than a working construction.

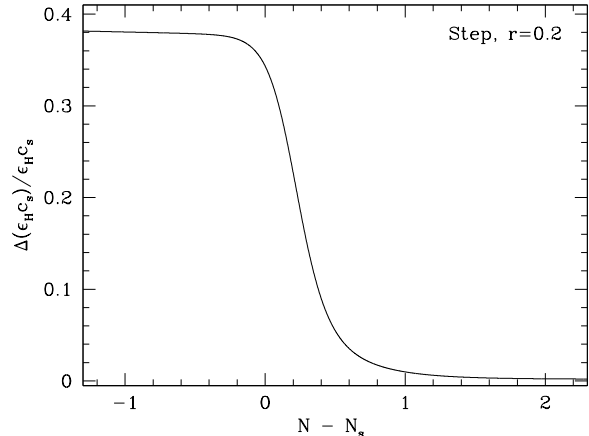


FIG. 2. Step in tensor-scalar ratio parameter  $\epsilon_{Hc_s}$  relative to no step, from the best fit  $r = 0.2$  solution centered at the efold  $N_s$  at which the inflaton crosses the step. Planck data favor a step that is traversed in about an efold.

produces a step in the quantity  $\epsilon_{Hc_s}$  that controls the tensor-scalar ratio. To keep this discussion model independent, we follow Ref. [14] and quantify the amplitude of the step by the change in this quantity

$$C_1 = -\ln \frac{\epsilon_{Hb} c_{sb}}{\epsilon_{Ha} c_{sa}}, \quad (6)$$

where “ $b$ ” and “ $a$ ” denote the quantities before and after the step on the slow roll attractor. In place of  $\phi_s$  we quote the sound horizon

$$s = \int dN \frac{c_s}{aH} \quad (7)$$

at the step  $s_s = s(\phi_s)$  and in place of the width in field space  $d$ , we take the inverse of the number of efolts  $N$  the inflaton takes in traversing the step

$$x_d = \frac{1}{\pi d} \frac{d\phi}{d \ln s}. \quad (8)$$

See Ref. [14, 15] for details of this description. We utilize the generalized slow roll technique [16–18] to calculate the power spectra of these models since at the step the slow roll approximation is transiently violated.

### III. JOINT FIT

We jointly fit the Planck CMB temperature results, WMAP9 polarization results, and BICEP2  $BB$  power spectrum results to models with and without steps in the tensor-scalar ratio parameter  $\epsilon_{Hc_s}$ .

We begin with the baseline best fit 6 parameter slow-roll flat  $\Lambda$ CDM model with  $r = 0$ . Throughout we fix these cosmological parameters to  $A_s = 2.216 \times 10^{-9}$ ,  $n_s = 0.962$ ,  $\Omega_c h^2 = 0.1203$ ,  $\Omega_b h^2 = 0.022$ ,  $h = 0.67$ ,  $\tau =$

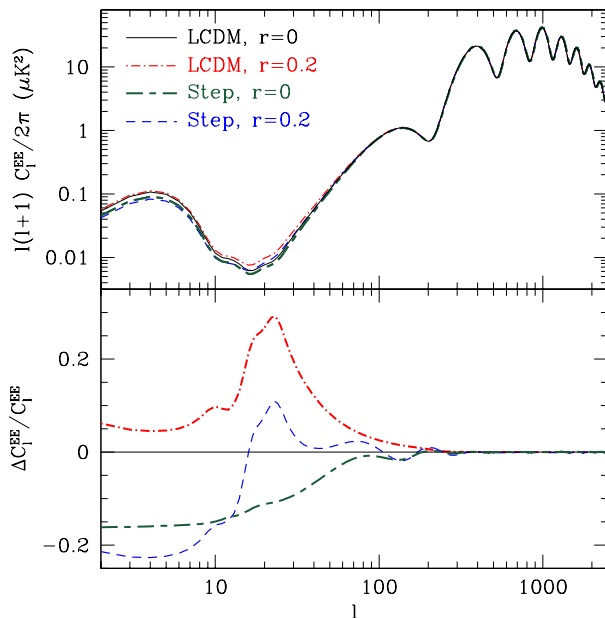


FIG. 3.  $EE$  power spectrum for the models in Fig. 1 showing the change from the best fit  $r = 0$   $\Lambda$ CDM power spectrum. Excess  $E$ -modes from the tensors at  $r = 0.2$  are partially compensated by the step at  $\ell \gtrsim 30$  while changes at lower  $\ell$  can be altered by changing the reionization history. Preference for removing power at substantially smaller  $r$  would predict a deficit of power as the  $r = 0$  model shows.

$r$	$C_1$	$s_s(\text{Mpc})$	$x_d$	$-2 \ln \mathcal{L}_P$	$-2 \ln \mathcal{L}_B$	$-2 \ln \Delta \mathcal{L}_{\text{tot}}$
0	0	-	-	9805.8	55.2	37.1
0	-0.17	360.9	1.41	9801.4	55.2	32.8
0.1	0	-	-	9809.8	15.4	1.4
0.1	-0.23	365.0	1.37	9800.0	15.5	-8.3
0.2	0	-	-	9816.3	7.6	0
0.2	-0.32	365.3	1.43	9799.7	7.6	-16.6

TABLE I. Likelihood for models with tensors and steps with other cosmological parameters fixed.  $\mathcal{L}_P$  is the likelihood for the Planck low- $\ell$  spectrum, high- $\ell$  spectrum and WMAP9 polarization;  $\mathcal{L}_B$  is that for the BICEP2  $BB$  likelihood. The change in the total is quoted relative to the  $r = 0.2$  no feature case.

0.0925. Foreground parameters for the Planck likelihood are chosen as in Ref. [14].

As shown in Tab. I, this  $r = 0$  model is strongly penalized by the BICEP2 data. Moving to the  $r = 0.2$  model with the same parameters removes this penalty at the expense of making the Planck likelihood worse by  $2\Delta \ln \mathcal{L} = 10.5$  due to the excess in the  $\ell \lesssim 100$  temperature power spectrum shown in Fig. 1.

Next we fit for a step with parameters  $C_1$ ,  $s_s$ ,  $x_d$  controlling the amplitude, location and width of the step. The best fit model at  $r = 0.2$  more than removes the penalty from the temperature excess for Planck while fitting the BICEP2  $BB$  results equally well. The net result is a preference for a step feature at the level of  $2\Delta \ln \mathcal{L} = -16.6$  over no feature. Note that we have fixed

the other cosmological parameters to their values without the step. With the addition of the step, there remains a small high- $\ell$  change in the well-measured acoustic regime in Fig. 1. Thus the likelihood may in fact increase in a full fit. Conversely, we do not consider any compromise solutions where cosmological parameters ameliorate the tension without a step. We leave these considerations to a future work.

The best fit step also predicts changes to the  $EE$  polarization. Like the  $TT$  spectrum, the excess power from the tensor contribution is partially compensated by the reduction in the scalar spectrum for  $\ell \gtrsim 30$ . Changes at smaller multipoles are mainly due to changing the reionization signal at fixed  $\tau$ . The differences will therefore be largely degenerate with changes in the ionization history.

Due to potential contributions from foregrounds in the BICEP2 data which may imply a shift to  $r = 0.16^{+0.06}_{-0.05}$  [1], we also test models at  $r = 0.1$  which would formally be in tension with the BICEP2 likelihood without foreground subtraction. Even in this case, the Planck portion of the likelihood improves with the inclusion of a step though the preference is weakened to  $2\Delta \ln \mathcal{L}_P = -9.8$  versus no step. At  $r = 0$ , the Planck data still prefers a step to remove power at a reduced improvement of  $2\Delta \ln \mathcal{L}_P = -4.4$ , a fact that was already evident in the Planck collaboration analysis of anticorrelated isocurvature perturbations [19]. Such an explanation should also help resolve the tensor-scalar tension albeit outside of the context of single-field inflation. Interestingly, the addition of tensors at  $r = 0.2$  in fact further helps step models fit the Planck data due to the changes shown in Fig. 1 independent of the BICEP2 result.

#### IV. DISCUSSION

A transient violation of slow-roll which generates a step in the scalar power spectrum at scales near to the horizon size at recombination can alleviate problems of predicted excess power in the temperature spectrum, present already in the best fit  $\Lambda$ CDM spectrum, and greatly exacerbated by tensor contributions implied by the BICEP2 measurement. Such a step may be generated by a sharp change in the speed of the rolling of the inflaton  $\epsilon_H$  or by a sharp change in the speed of sound  $c_s$  over a period of around an efolding which combine to form the tensor-scalar ratio. Preference for a step from the temperature power spectrum is at a level of  $2\Delta \ln \mathcal{L}_P = -16.6$  if  $r = 0.2$  and is still  $-9.8$  at  $r = 0.1$ , the lowest plausible value that would fit the BICEP2 data.

Such an explanation makes several concrete predictions. Since slow-roll is transiently violated in this scenario, there will be an enhancement in the associated three-point correlation function. However, we do not expect this signal to be observable as it impacts only a small number of modes [8, 9].  $E$ -mode fluctuations on similar scales would be predicted to have a smaller enhancement than with tensors alone, which is a testable prediction of

this explanation.

While we have used a DBI type Lagrangian to illustrate the impact of a change in the tensor-scalar ratio parameter  $\epsilon_{HC_s}$  due to a step in the sound speed, we do not expect that our results are dependent on this form. Transient shifts in the speed of sound have been found to occur in inflationary models where additional heavy degrees of freedom have been integrated out [20]. We leave investigation of specific constructions to future work.

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